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Research Paper

Influence of Steel Slag Aggregate Gradation on the Improvement of Concrete Properties

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ABSTRACT

Steel slag, as a by-product of the iron industry, is widely produced in the world. In this paper, steel slag from local furnaces is partially replaced as concrete aggregate to compensate for irregular consumption of raw material for concrete and reduce environmental impacts of waste slag. Six mix designs were considered, and three categories of aggregate size were selected to evaluate the aggregate replacement effect in the concrete samples. Sieve analysis, X-ray diffraction (XRD) analysis, aggregate porosity, slump, compressive strength, and microstructure analysis were implemented to investigate aggregates and concrete samples. The results showed that compressive strength and water absorption of the concrete with 20% aggregate replacement were 37.4 MPa and 3%. By 20% aggregate replacement, improvement in the compressive strength and reduction in the water absorption were observed. Increasing aggregate replacement to 40% reduced compressive strength by 62% and increased water absorption. In the concrete containing 62% of the replacement, the required compressive strength of 30 MPa, as design compressive strength, was achieved. However, although the pores in the slag aggregates can affect fresh and hardened properties of concrete, selecting an appropriate range of aggregates from the gradation curve can limit the side effects due to the pores.

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1. Introduction

Steel slag is a by-product (12-20%) that is produced from the steel production process. There are environmental problems related to burying or storing this material that can be solved [1-2]. The World Steel Association reported that global crude steel emissions in 2022 were 1878.5 million tons, indicating steel slag production exceeds 225 million tons [3]. The storage of steel slag of China, as the world's largest producer of crude steel, reached 1468 million tons in 2020 [4].

Management of these wastes to recycle and reuse steel slag is one of the most important challenges and problems in the steel industry, both in terms of the environment and in terms of the vast space occupied for its storage. One of the approaches to manage this waste is to utilize steel slag as a partial replacement for concrete aggregate [5-6]. It has superior mechanical performance and abrasion resistance compared to ordinary aggregates, resulting in its usage to the savings of natural resources derived from the valorization of waste. However, the gradation of slag aggregates and the replacement amount can be a challenge for concrete mix designers. It can improve concrete strength and durability, and due to its waste-material nature, therefore, researchers are interested in replacing natural aggregate with steel slag in concrete [7-8].

Liu and Guo in 2018 [9] reported applications of steel slag powder and steel slag aggregate in ultra-high-performance concrete (UHPC). They found that UHPC containing steel slag powder and steel slag aggregate can display satisfactory compressive strength with the cement replacement ratio of <10%. Sosa et al. in 2020 [10] showed self-compacting concretes with Electric Arc Furnace Steel Slags (EAFSS) that fulfill the demands such as flowability, stability, and mechanical properties required for this type of concrete, and conserving natural resources and cleaning the environment. Kumar and Soni in 2022 [11] compared the effects of steel slag aggregates over blended cement concrete. With increasing the proportion of steel slag in concrete, the strength of concrete increased while the slump value reduced. Khafaga et al. in 2014 [12] replaced up to 66.7% of concrete coarse aggregates with steel slag aggregates to access UHPC. Impermeability of the produced concrete was enhanced when using EAFSS coarse aggregates. In addition, EAFSS exhibited appropriate potential for several construction applications, such as aggregates for road construction and sub-bases, breakwater blocks, foundations, shoring walls, shields in nuclear plants, radiotherapy rooms, and radiation insulators for transporting.

Vishavkarma and Venkatanarayanan [13] reported the influence of the pore structure of foam concrete containing slag for improved durability performance. Their obtained results showed that increasing Ground Granulated Blast Slag (GGBS), up to 60%, decreased water absorption, porosity, chloride ion permeation, and resistivity. Moreover, drying shrinkage values decreased, whereas sorptivity decreased with increasing GGBS dosage up to 30%.

The conductivity of steel slag aggregate concrete makes it worthy of being electromagnetic shielding material due to the presence of ferrite oxides in the $FeO/Fe_3O_4/Fe$. It was mentioned that steel slag aggregate (SSA) is a more sustainable material compared to steel fiber [14]. Generally, by SSA treatment, mix design, mixing, and casting, the compressive, split tensile, and flexural strengths of ordinary concrete increased 10-30%, 10-60%, and 15-70%, respectively [15].

Aggregate gradation and its amount in concrete are among the most significant challenges to using SSA as the green material of waste recycling that leads to decreased landfill space. An available local resource of SSA, which was considered waste material, is noticed in the present study to be replaced for natural aggregate (NA) in concrete. This experimental program investigates the selection of an appropriate range of aggregates from the SSA gradation curve and its influence on the concrete properties.

2. Materials and methods

2.1. Materials

Cement and aggregates prepared for concrete mix designs are described in this part. Type 1 Portland cement according to ASTM C150 [16] was used in this project. The physical and chemical characteristics of cement are presented in Table 1.

Table 1. Chemical and physical characteristics of Portland cement type 1-425 [17]

Chemical Composition (%)										Fineness (cm2/g)
SiO_2	Al_2O_3	Fe2O3	CaO	SO_3	MgO	K_2O	Na_2O	L.O.I	C3A	
20.35	5.3	4.1	63.25	2.44	2.11	0.71	0.21	1.05	7.1	3200±100

Figs. 1 and 2 show the process resulting in local furnace waste slag (LFWS) and waste slag aggregates. The waste slag aggregates are outputs of the process in which metallic products are produced. The maximum size of the available slag particles was 40 mm, but the maximum size of SA for concrete was 19 mm. As in Fig. 3 and Table 2, after a sieving analysis, SSAs were classified in four categories for concrete.

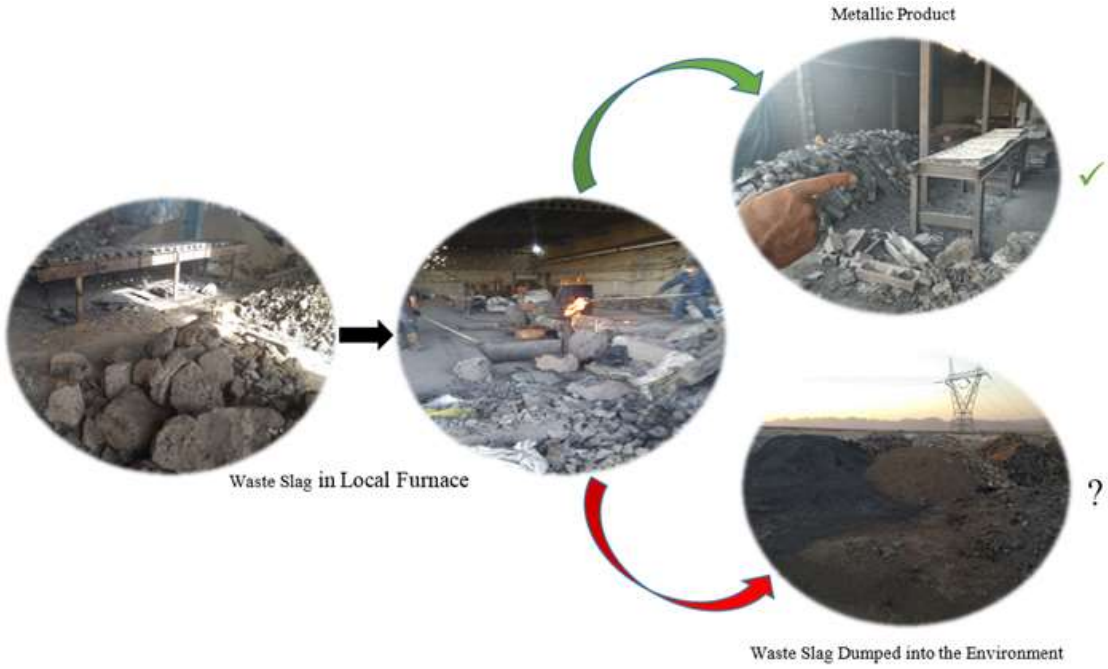


Fig. 1. Overview on the process resulting in LFWS

Fig. 2. Waste slag aggregates

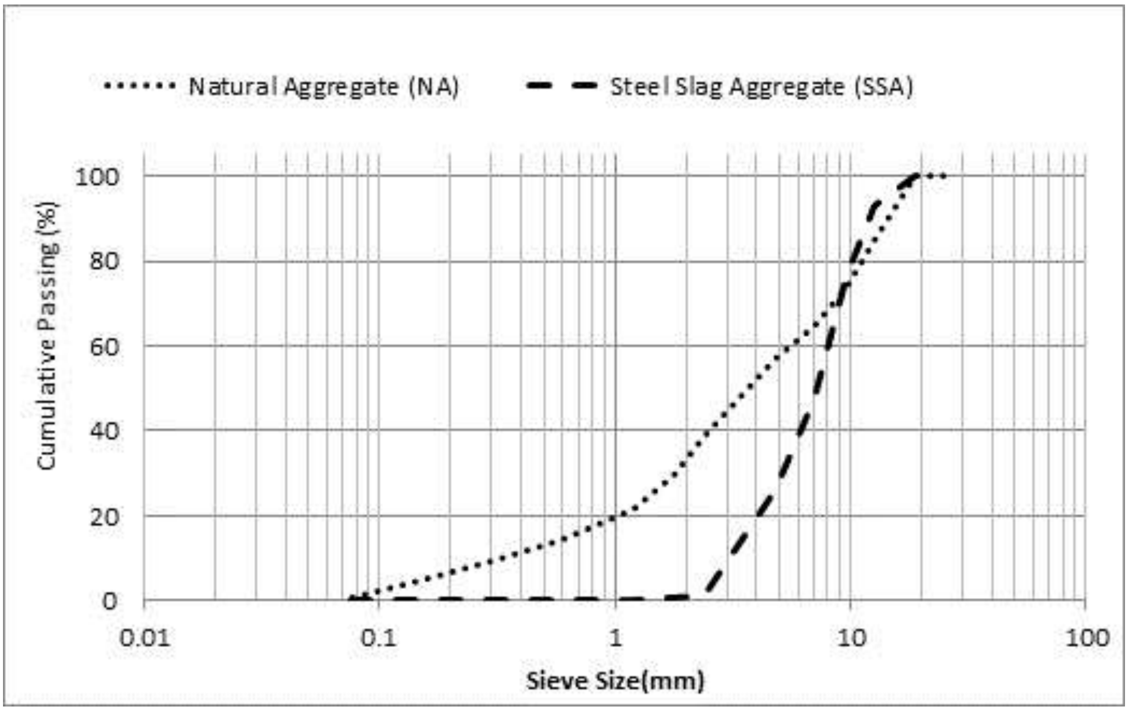


Fig. 3. Size distribution curve of the SSA and NA

Table 2. Classification and local application of SSA from local furnaces in Najafabad city

Classification	Aggregate size (mm)	Local application	Amount in unit weight (%)
Gravel	5-19	Block-case; Slope	35
Coarse sand	3-5	Slope in short buildings	30
Fine sand	100 µm -3	Sandblasting; Foundry recycling	30
Iron powder (Iron soil)	<100 µm	Agricultural fertilizer	5

In this research, three size groups of SSA, including gravel of 5-19 mm, coarse sand of 3-5 mm, and fine sand of 100 µm-3 mm, were substituted for natural aggregates (NA) of similar size. Iron powder particle size was <100 µm and removed from the aggregate replacement process. Gradation of SSA and NA was performed according to the ASTM C 136 [18]. Water absorption and specific mass density tests of coarse aggregate and fine aggregate were performed based on ASTM C 217 and C 218 [19-20], and the wear resistance of coarse aggregate was evaluated using Los Angeles (L.A.). The abrasion test according to ASTM-C131 [21] is shown in Table 3.

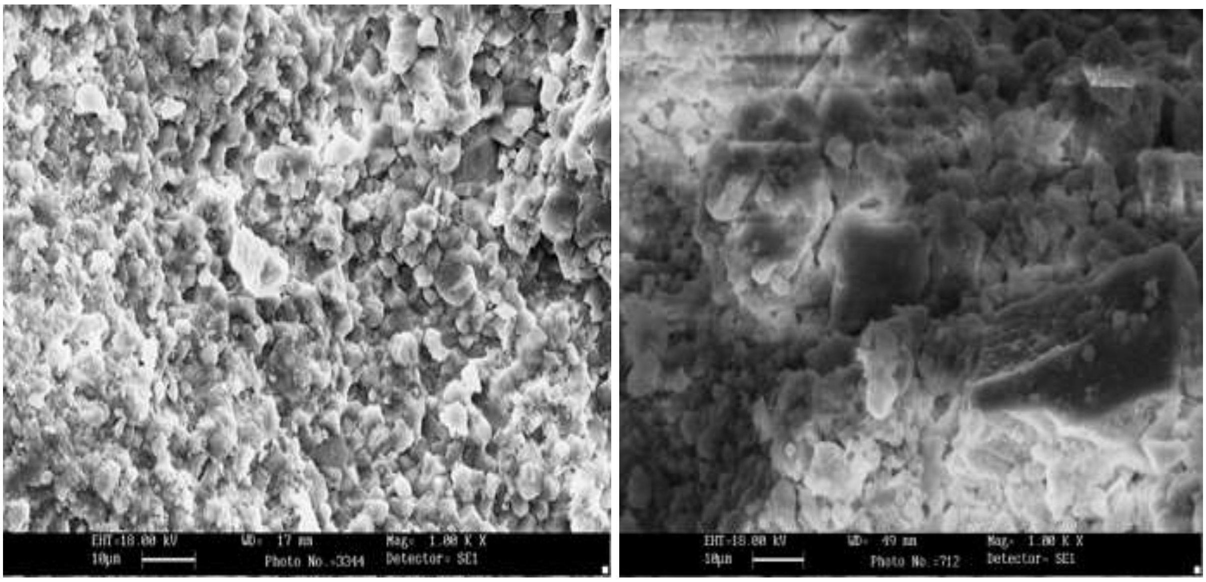
Table 3. Comparison of physical characteristics of NA and SSA

Type of Aggregates	Classification	Density (Kg/m^3)	Water Absorption (%)	Los Angeles Abrasion (%)
Slag	Gravel	2560	4.2	36
	Coarse sand	2520	3	
	Fine sand	2520	3	
Natural	Gravel	2670	0.8	30
	Coarse sand	2580	2.33	
	Fine sand	2560	3	

The percentage of water absorption in SSA is higher than NA. Also, the abrasion index of SSA is 36%, for which, according to the Iranian National Standardization Organization–INSO-448 [22], its critical value is 30% for concretes exposed to abrasion and 50% for other structures. The abrasion resistance of SSA of blast furnace and electric arc furnace slag aggregates was previously reported to be between 8 and 15% [23-24].

The appearance and microstructure of SSA and NA are compared in Figs. 4 and 5. Slag coarse sand and slag fine sand have rough texture compared to the natural sand, while natural coarse sand and natural fine sand have smooth surfaces similar to the natural aggregates of the same size in the previous research [23, 25-26].

Fig. 4. Appearances comparison of SSA and NA



(a) Slag Gravel (b) Natural Gravel

Fig. 5. SEM images of slag and natural gravel

2.2. Mix designs

In order to investigate the effect of slag aggregates, as in Table 4, six different mixture ratios were designed. The variables in the mixtures were the amount of cement and the ratio of water to cement, but the amount of water was fixed. In the present research, the design strength was to be 30 MPa. Therefore, for each mix design, 430 kg/m³ of cement and 202 kg/m³ of water were considered according to ACI 211.1-91 [27]. In these mix designs, natural (N) and/or slag (S) aggregates were used. In this research, each mix design is designated by a "Mix ID" in which "N" refers to "Natural" type of aggregate and "S" refers to the "Slag" type of aggregate. In addition, in each "Mix ID," the first letter stands for gravel, the second letter stands for coarse sand, and the last letter stands for fine sand. The amount of materials used in the mix designs is with respect to the reference mix design "N-N-N" that was prepared based on ASTM C 211.1-91 [27].

Table 4. Properties of mix designs (Units in kg) according to ASTM C 211.1-91

Mix ID	Cement	Natural			Slag			water	Slag Replacement (%)
		Gravel	Coarse Sand	Fine Sand	Gravel	Coarse Sand	Fine Sand		
N-N-N	430	648.6	331.3	773.1	0	0	0	202	0
S-S-N		0	0	666.1	1107.7	0	0		63
S-S-S		0	0	0	1107.7	0	666.1		100
S-N-N		0	326	761	706	0			40
N-S-S		703.8	0	0	0	326	760.8		62
N-S-N		649	0	773	0	331	0		20

3. Results and discussion

3.1. XRD analysis

As can be seen from the XRD patterns, the most crystalline phases of steel slag are iron III oxide and quartz (Fig. 6). The presence of wustite brown millerite and larnite, can be attributed to the initial composition of the steel slag [28]. However, natural fine aggregate mainly contains quartz, calcite and portlandite that were already mentioned in some previous research [29].

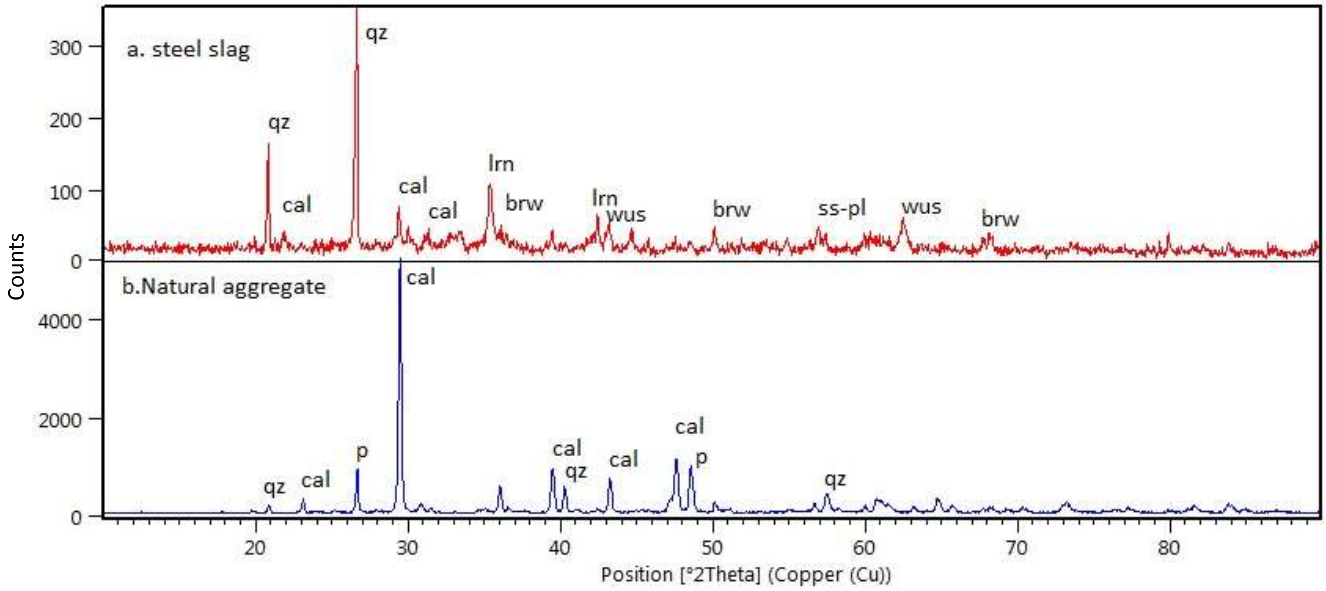


Fig. 6. X-ray diffraction (XRD) patterns (a.) steel slag and (b.) natural fine aggregate. (wus = wustite, ssSpl = spinel solid solution, chr = chromite, brw = brownmillerite, Lrn = larnite, Cal = calcite, qz = quartz, p= portlandite)

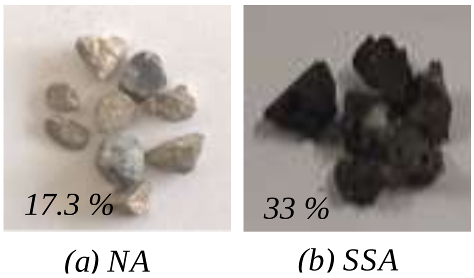


Fig. 7. Porosity of aggregates

3.2. Porosity

One of the important factors for the fabrication of dense concrete is limiting porosity aggregates, while to provide lightweight concrete, porous aggregates can be useful. To calculate the porosity (Ƹ) in percent, as by Equation (1), a high wettability solvent such as water and ethanol was used. This is also known as the liquid displacement method (Archimede's Principle) [30].

$$Ƹ= (V_1-V_3)/(V_2-V_3) \quad (1)$$

In Equation (1), V_1= initial volume; V_2= secondary volume after immersion of aggregate; V_3= final volume after removing aggregate. Fig. 7 showed the porosity of NA and SSA. It was observed that the porosity of NA was 17.3% and the porosity of SSA was 33%. Porosity of SSA is almost doubled in comparison to NA.]

3.3. Concrete slump and strength

The relationships between the replacement percentage of SSA, slump, water absorption, and strength are presented in Table 5. In general, by replacing slag aggregates, concrete slump (flowability) is decreased, which could be due to the water absorption by slag aggregates. The minimum slump (25 mm) is observed when replaced slag is for gravel and coarse sand as S-S-N. Consequently, water absorption is increased in all mix designs with slag aggregates. These results could be attributed to the porous structure of the slag aggregates. Accordingly, a decrease in the compressive strength can be due to the porous structure of concrete due to the slag aggregates. By increasing the replacement amount of casting slag aggregates from 20 to 40%, an increase in water absorption is observed. However, a constant trend is observed for the replacement > 40%. The higher compressive strength at both 7-day and 28-day ages is for 20% slag replacement (N-S-N). However, by 40% and 62% replacement slag replacement in S-N-N and N-S-S, respectively, compressive strength is still higher than the designed compressive strength that was 30 MPa.

Table 5. Properties of mix designs under fresh and hardened states

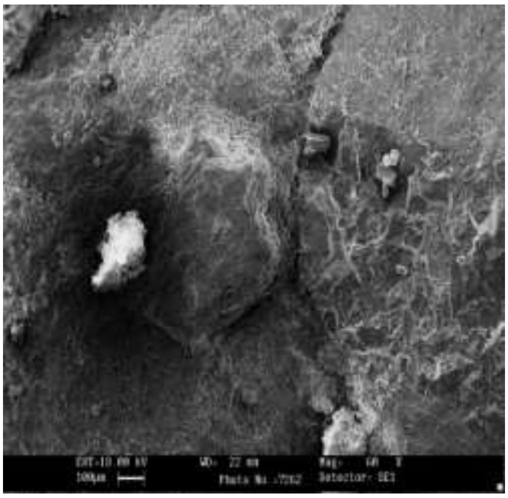
Mix design	Replacement level (%)	Slump (mm)	1-hour water absorption (%)	Compressive strength (MPa)	
				7-day	28-day
N-N-N	0	100	3.3	30.0	36.0
S-S-N	63	25	4.1	25.5	26.9
S-S-S	100	45	4.2	27.4	29.9
S-N-N	40	50	4.2	27.1	32.9
N-S-S	62	77	4.0	30.2	31.9
N-S-N	20	63	3.1	33.4	37.4

As in Table 5, the mix design containing natural gravel, coarse slag sand, and natural fine aggregates (N-S-N) has the highest 28-day compressive strength of 37.4 MPa among concretes containing slag aggregates. The highest replacement with 100% in the S-S-S mixture has caused a drop in the compressive strength from 36 MPa to 29.9 MPa. These results highlight the significance of the combination of natural and slag aggregates to reduce the side effects of slag aggregates due to their porosity.

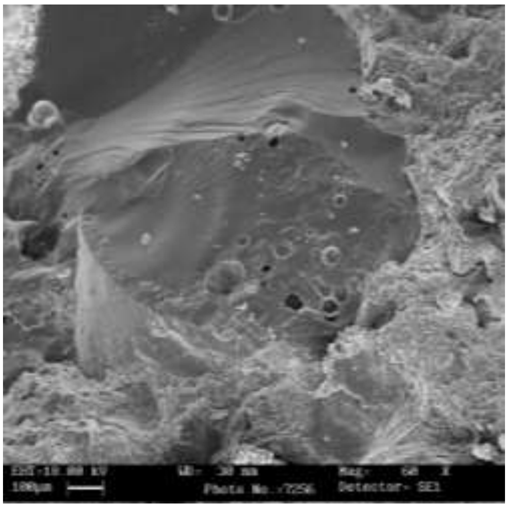
Results of 1-hour water absorption percentage of concrete samples containing NA and SSA are also presented in Table 5. Replacement of slag aggregates instead of natural aggregates led to an increase in the percentage of water absorption. The percentage of water absorption for the S-N-N sample after 1-hour immersion is 4.2%, indicating a 28% increase in the water absorption compared to the N-N-N sample. The lowest percentage of water absorption was observed in concrete containing 20% replacement of slag aggregate (N-S-N) with a value of 3.1%. While in concrete with natural aggregate, the percentage of water absorption after 1 hour is equal to 3.3% (7% drop). In all concretes, the percentage of water absorption in 1 hour is less than 5%, and they are in the group of concrete with medium and low permeability based on ASTM C642 [9].

3.4. Microstructure of Concrete

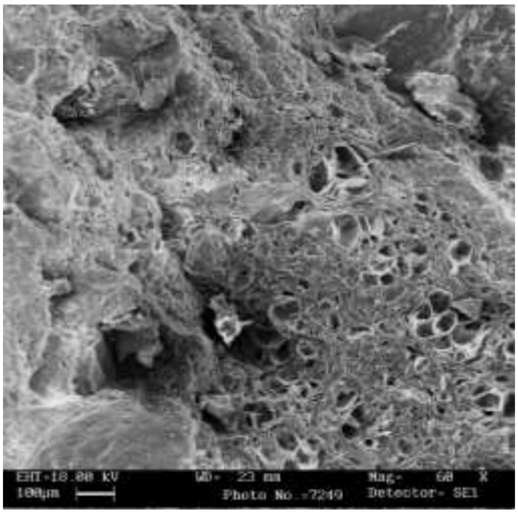
Results of scanning electron microscopy (SEM) images on 28-day concrete samples containing natural and slag aggregates are presented in Fig. 8. As stated, the highest replacement with 100% in the S-S-S mixture caused a drop in the compressive strength from 42 MPa to 30 MPa. While according to Fig. 8 (a), there is no specific porosity in the natural aggregates, as in Fig. 8 (b), the high porosity in coarse slag aggregates can be the cause of reducing compressive strength. Replacement of 62% of slag aggregate (N-S-S) resulted in a compressive strength of 30 MPa. In Fig. 8 (c) for the N-S-S sample, the texture of the sample is not as homogeneous as that of the concrete with ordinary aggregates, but there is no large porosity. In this concrete, a drop in strength has occurred due to the presence of aggregates with small porosity.



a) N-N-N



b) S-S-S



c) N-S-S

Fig. 8. Electron microscope observation of some samples

4. Conclusion

The purpose of this research was to investigate the replacement of slag aggregates of local furnaces in concrete. The results showed that in the concrete with coarse sand slag (20% of the total aggregate was replaced), the lowest drop in the compressive strength and slump occurred, and the minimum increase in the water absorption happened. In addition, in the concrete containing 62% of the replacement, which contains natural sand, coarse sand slag, and fine sand slag, the required values of durability and mechanical characteristics are provided, and it can be recommended for concrete material. The results of the loss of compressive strength and durability in concretes containing slag aggregates and concretes containing fine slag were confirmed by examining the microstructure. Slag aggregates have small pores, and it can be the reason for reducing mechanical strength and durability.

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Competing interests

The authors declare no competing interests.

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